Faster than Light

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The transmission of signals faster than light can be observed for am/fm modulated frequency signals (radio signals) when passing them through a narrow waveguide (metal tube). See figure 1.

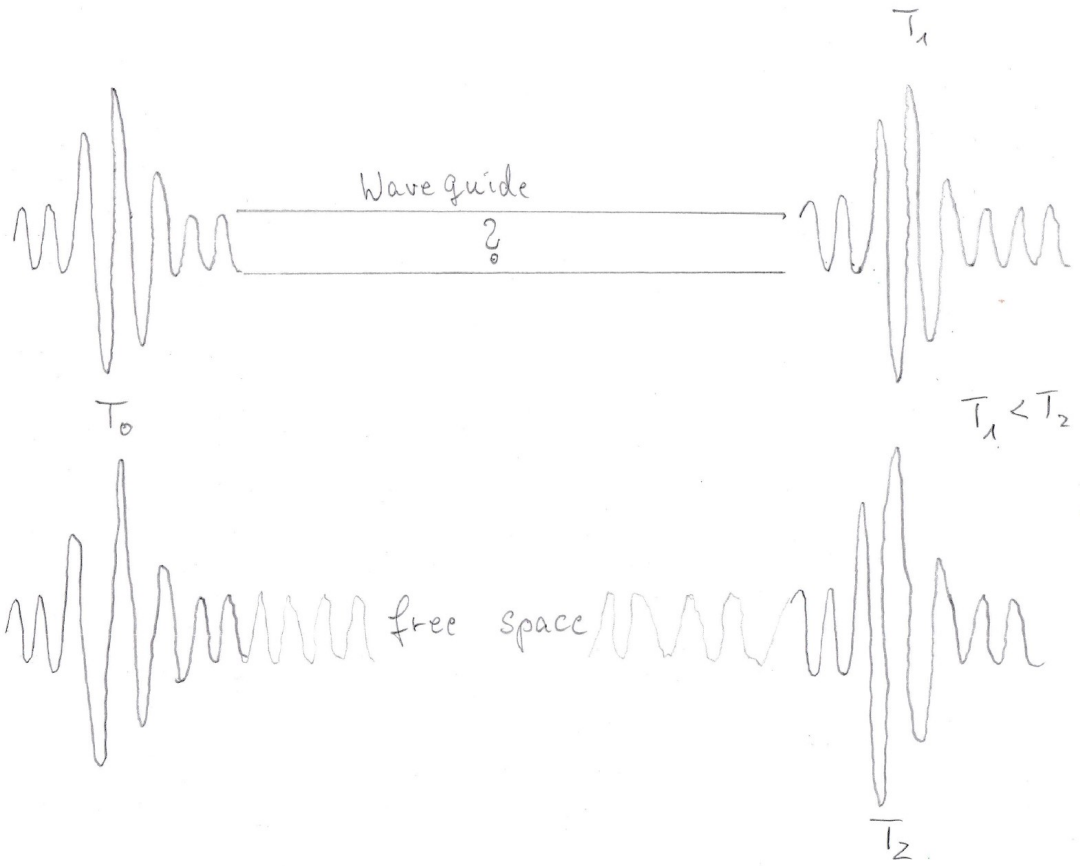

figure 1

One (including me) usually brushes this aside with reference to the "phase velocity" as opposed to the "group velocity". This is, however, completely brainless. Phase velocity comes in when one has a spatially extended energy distribution and looks at the displacement of equal phase along a given direction. A simple example is a wavefront impinging on a liner oblique to the front's direction of motion (figure 2).

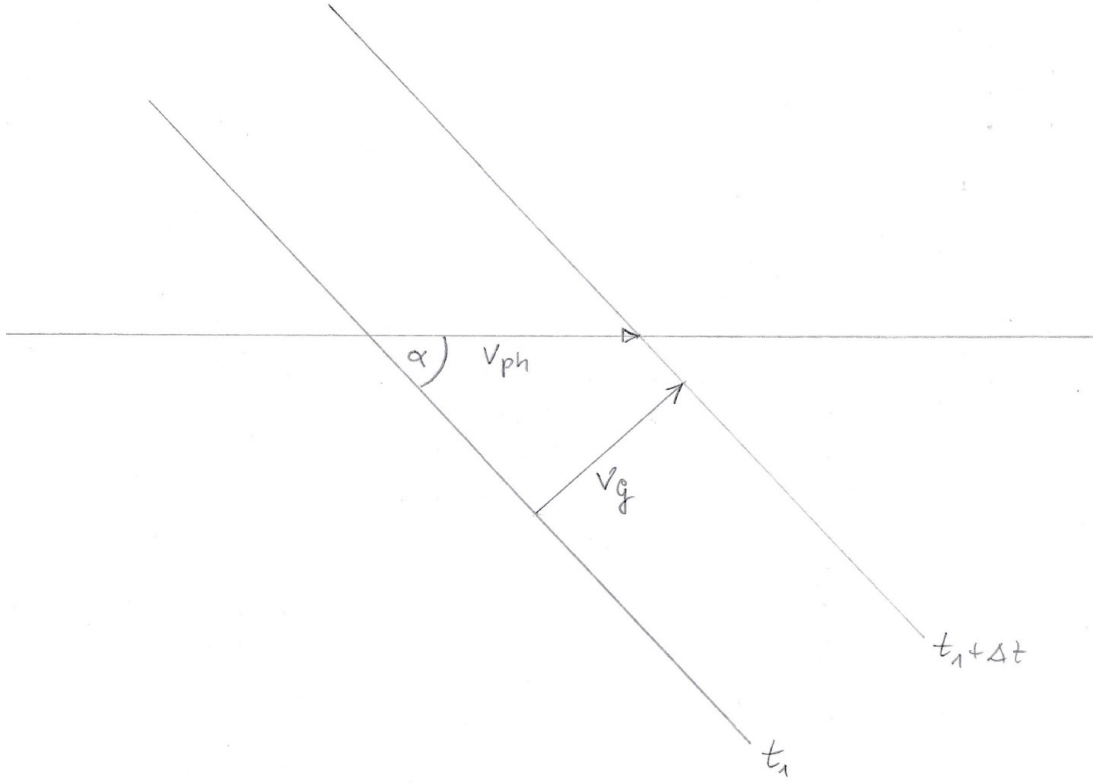

figure 2

An identifiable energy volume displaces itself parallel to the liner at velocity

$v_{gr} = c \sin\alpha < c$

The phase displaces itself along the liner at velocity

$v_{ph} = c / \sin\alpha > c$

giving $v_{gr} v_{ph} = c^2$

What does that have to do with a perfectly localisable wavepacket riding on a carrier frequency? We have to admit that we are in the presence of genuine energy transfer at superluminal speeds and the task is to understand how this is possible in the framework of electrodynamics.

Let us, therefore, look at electromagnetic fields in a metal waveguide (figure 3). Of course, we always restrict ourselves to one single mode and one longitudinal dimension (x) in all that follows.

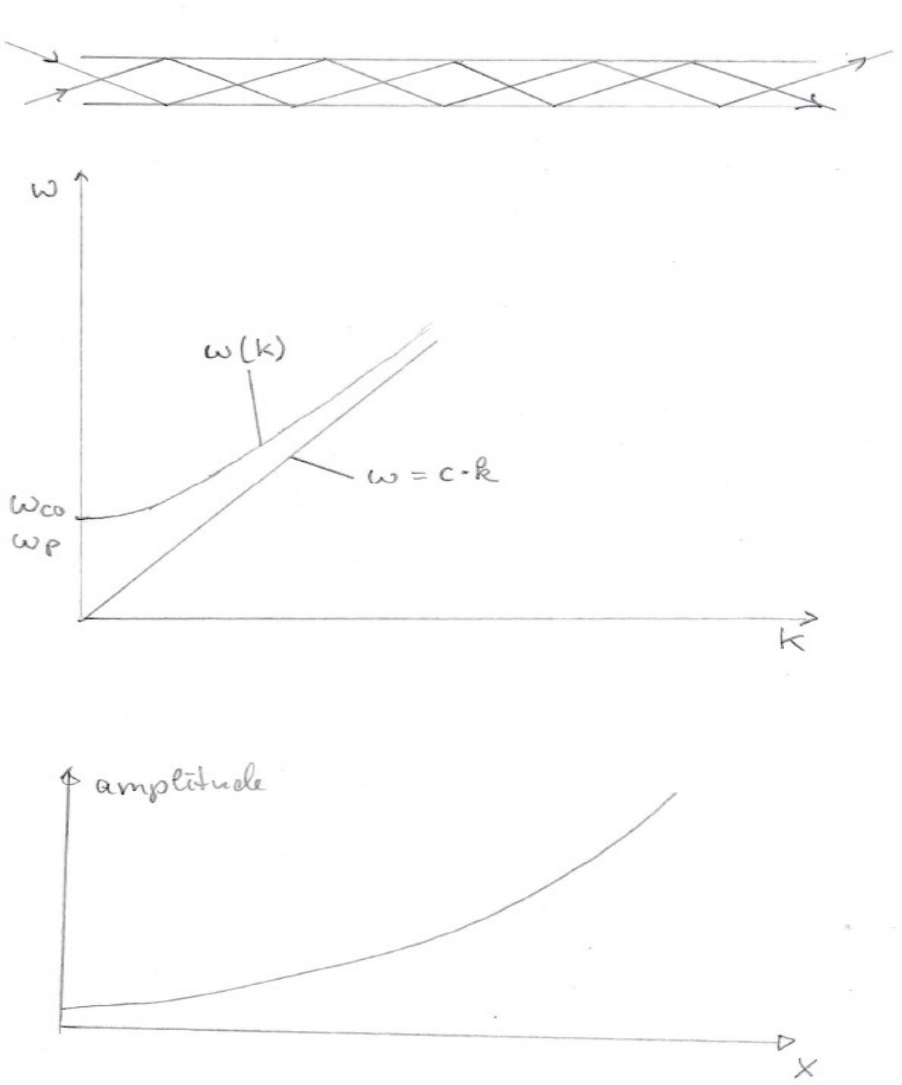

figure 3

Wavepropagation can be advantageously viewed as an oblique wavefront reflecting itself down the guide. (figure 3 top)
The dispersion relation is (figure 3 middle)

$\omega(k) = c\ \sqrt{(k^2 + k^2_{CO})}$

We have the well-known cut-off frequency given by the waveguide width and no wave can propagate at a frequency below it.

Yet, we can perfectly write down a solution at lower frequency with an exponential decay (fig. 3 bottom), which we cannot construct from the "allowed" frequency range functions.

How come ?

"A differential equation is complete only with boundary conditions"

Let us give this empty statement some content.
Quite evidently boundary conditions *are* given in the transverse direction with the metal guide walls. Still, our exponential solution perfectly respects them.
Are we then not entitled to any boundary conditions we desire in the longitudinal direction?
The answer is no and the reason is that we require physical mathematical operators (A) to be hermitean (self-adjoint) such that for any (in general complex) functions $\varphi(x)$, $\psi(x)$, their scalar product obeys

$$(\int \varphi^* A\, \psi)^* = \int \psi^* A\, \varphi$$

Let us take the operator A to be the Laplacean $\Delta = \partial^2_x$, easy in one dimension

$$\int \varphi^*\, \partial^2_x\, \psi = \varphi^*\, \partial_x\, \psi \,\big|^t_b - \partial_x\, \varphi^*\, \psi \,\big|^t_b + (\int (\partial^2_x \varphi^*)\, \psi) = \varphi^*\, \partial_x\, \psi \,\big|^t_b - \partial_x\, \varphi^*\, \psi \,\big|^t_b + (\int \psi^* (\partial^2_x \varphi)\,)^*$$

(t,b) refer to the top and bottom boundaries

The first two boundary terms have to disappear which leaves us only with two choices of boundary conditions:

fixed boundary condition with any $\psi(x_{bound}) = 0$

periodic boundary condition with any $\psi(x_t) = \psi(x_b)$

In one dimension, for an interval [-L, +L], we can give a basis set by sine and cosine functions, see figure 4

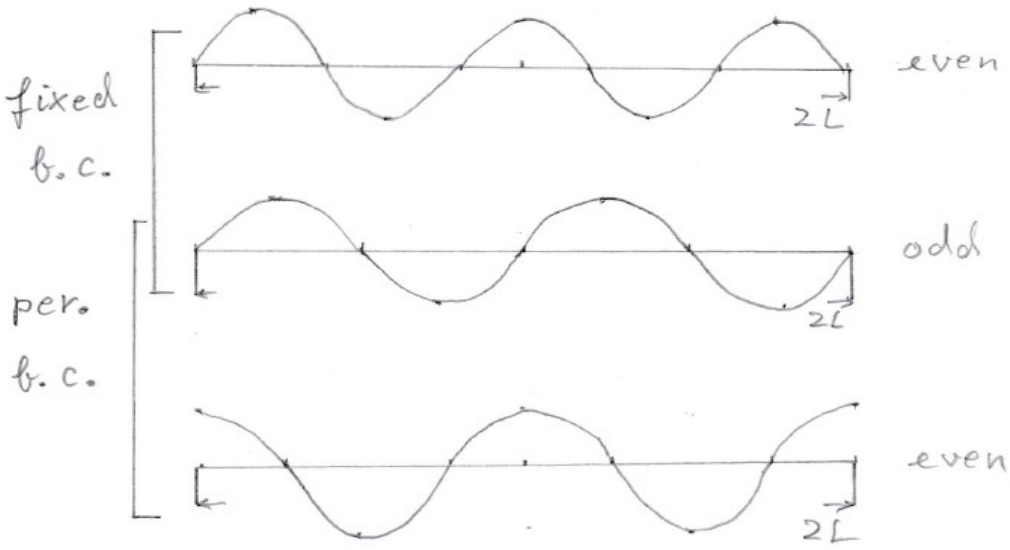

figure 4

For *fixed* b.c. we have functions of even symmetry (around x = 0) with cosines of period
$(2n + 1)\ \lambda/2 = 2L$
and functions of odd symmetry with sines of period $n\ \lambda = 2L$ (n integer)

For *periodic* b.c. we have functions of odd symmetry with sines of period $n\ \lambda = 2L$
and functions of even symmetry with cosines of period $n\ \lambda = 2L$ (n integer).

We see that each boundary conditions contains "as many" basis functions and that they share "half" of the basis.

This is important for any numerical simulation as we have to treat a situation where the waveguide has finite length D = 2d between [-d, +d] and radiation enters from both sides from open space.
In what follows we will use an effective model using a scalar (complex) wavefunction that obeys

$- \partial^2_t \psi = - \partial^2_x \psi + m^2(x) \psi$

with $m = \omega_{CO}$ for $x \in [-d, d]$, m = 0 otherwise

We have manifest Lorentz invariance and we obtain the dispersion relation of the waveguide in the waveguide section as seen above (figure 3).

Let us now look at a high-frequency regime $\omega >> \omega_{CO}$ and compare the propagation of a wavepacket in a waveguide and in a dielectric.

In a dielectric, the wavelength *shortens* as compared to the free-space wavelength.

In the waveguide, the wavelength *lengthens* as compared to the free-space wavelength.

In both cases, group velocity is smaller than c.
See figure 5.

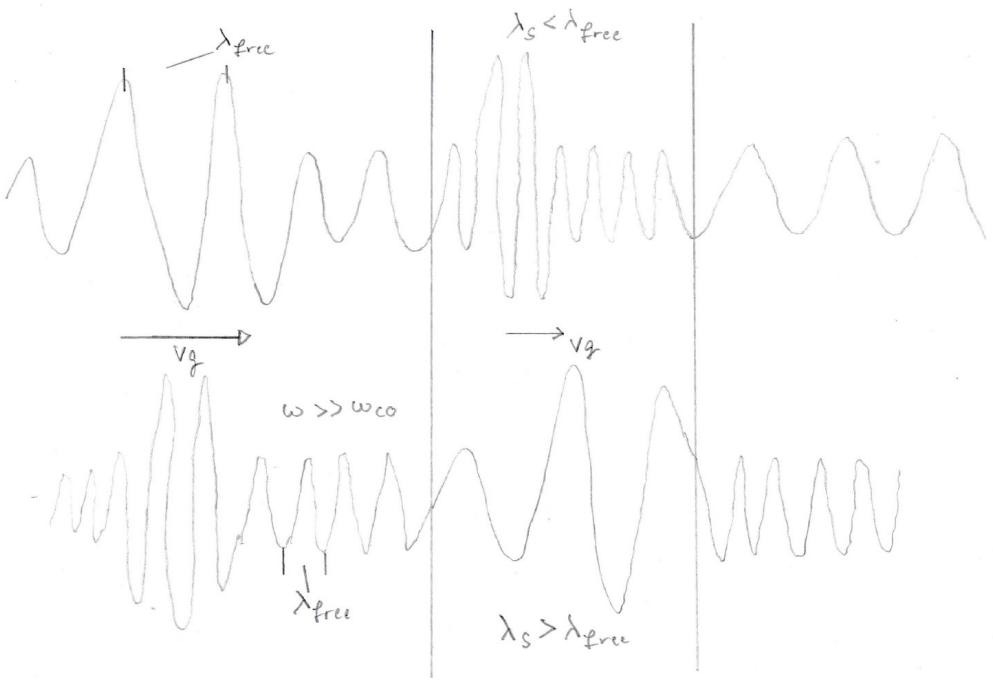

figure 5

For a dielectric this is true down to frequency zero.

For a waveguide, however, the situation changes when the lengthened wavelength becomes greater than the waveguide length.

So, as we approach the cutoff frequency from above, we get a behaviour as depicted in figure 6. Our chosen symmetry allows us to depict even and odd basis functions that respect the wave equation above.

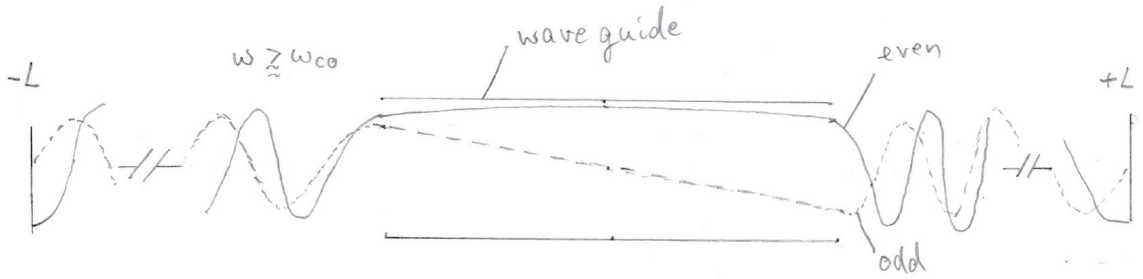

figure 6

The situation continues smoothly as we go below the waveguide cutoff frequency (figure 7). The only difference being that this behaviour is now *independent of waveguide length.*

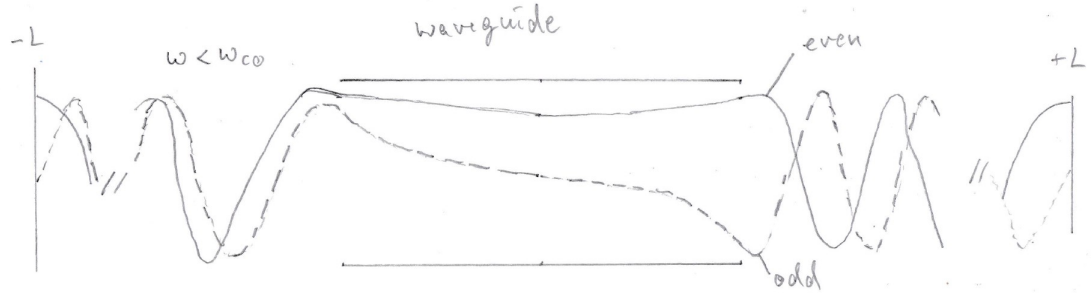

figure 7

We are now in a position to answer the initial riddle of "what happens in the waveguide".
The incoming modulation (wavepackage) is a frequency distribution narrowly centered around the carrier frequency. These frequencies will be below the waveguide cutoff.
All of these frequencies will connect to the other side as depicted in figure 7 and this gives a behaviour sketched in figure 8.

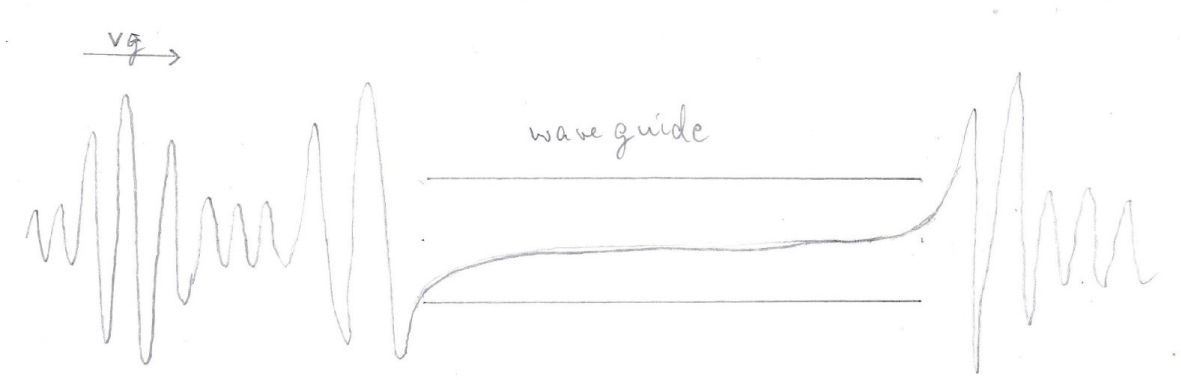

figure 8

The wavepackage does not enter the waveguide at all and all notions of group velocity are inapplicable there.
Instead, it "leaps over " the waveguide, allowing at most one node inside.
This also answers the question of "how fast" the transmission actually is.
From figure 7 we see that the basis functions connect either "without" delay to the other side (even functions), or connect with a delay of a half-period (odd functions).
The delay of transmitting a modulation will then be below a half-period of the carrier frequency, independent of waveguide length.

It goes without saying that all of these remarks have to be validated by a competent numerical simulation, as we will have reflections and outgoing signal reductions.

So, in conclusion, we can answer the question "is superluminal energy transport possible?" with a resounding

yes

Applications (?)
Is there any use to superluminal signal transmission?
Maybe some high-end parallel computing issues to reduce communication delays between processors.
When you find nothing useful, why not head for defence? Target acquisition from several points can be transmitted saving some nanoseconds.
Or, even worse, computer stock market trading, getting info updated faster than the competition.

Still, there might be a rather esoteric but real application: interstellar communication.
In figure 3, we noted ω_p with hindsight. It is the *plasma* frequency which has the same dispersion relation. Space is filled up with tenuous, extremely thin plasma whose ctoff frequency can well go down to just several Hertz. If a carrier frequency is already present, one can introduce a modulation and transmit it across space, with little delay, as we saw above.
I leave it to the reader to find how long it would take to transmit Beethoven's "Song of Joy".